Real-Time Implementation of a Matched-Field Tracker in an Autonomous Submerged Target Trip-Wire System

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ABSTRACT

Passive acoustic matched-field tracking (MFT) has been used to detect, track, and classify submerged sources operating near bottom-deployed or vertical hydrophone arrays. The feasibility of implementing an autonomous, real-time MFT tracker has been limited by many factors including algorithm complexity, limited battery capacity, and the inability to maintain accurate in situ hydrophone array element locations. Hydra project scientists and engineers developed a solution to this problem. A sensor and processing system was designed and deployed during a recent international sea test and demonstrated the practicality of using a sparse acoustic array to act as a trip-wire surveillance system. This paper describes the sensor and processing system, the at-sea deployment method, and also details real-time tracking and processing results against a towed-source target.

INTRODUCTION

Naval commanders must work against an ever-quieting submarine threat in an attempt to maintain underwater situation awareness. Contemporary, underwater passive acoustic surveillance systems help clarify this picture and, in so doing, are expected to (a) operate in complex acoustic environments; (b) be lightweight, low power, and low cost; (c) be capable of operating covertly, and (d) be mostly autonomous.

Key situational information can be provided to naval commanders by a trip-wire system (Figure 1) that indicates when a submerged, submarine-like sound source has just passed over or nearby the acoustic sensors. Networking multiple trip-wire systems form extended barriers.

Two autonomous, low-power, lightweight tripwire prototypes, Hydra and Kelp (Figure 1), have been designed and tested at sea against a submerged, towed, acoustic source. Hydra is a 650-meter, seafloor, horizontal line array (HLA), with six non-uniformly spaced hydrophones and eight non-acoustic (magnetic, tilt, and depth) sensors. Kelp is a 70-meter, vertical line array (VLA) with six uniformly spaced acoustic and four non-acoustic sensors. Compared to Kelp, Hydra's long horizontal baseline provides better x/y target estimation, while Kelp's vertical orientation provides better depth discrimination than Hydra. The matched-field tracking (MFT) algorithm [1 and 2] used in each design requires accurate array element location (AEL). Hydra uses a novel semi-autonomous time-of-arrival-based AEL estimator, while Kelp autonomously performs AEL in real time using tilt, compass, and pressure measurements taken along the array.

HYDRA AND KELP ENGINEERING

Hydra and Kelp are composed of similar components. In both systems, a string of acoustic and non-acoustic sensors are connected to a node (Figure 2). The node generates timing signals for time-division multiplex synchronization of sensor data. The received digital acoustic and non-acoustic data are processed by a 32-bit floating-point digital signal processor (DSP) and recorded to a hard-disk drive for postmortem analysis. DSP-generated target tracks are then reported via a telesonar [3] link.

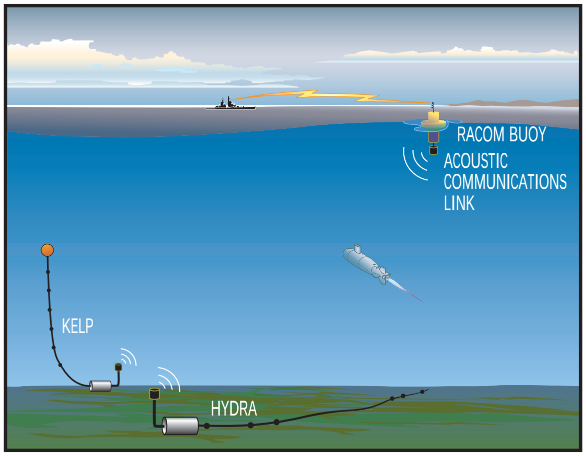

FIGURE 1. Hydra and Kelp operational concept. These two array systems autonomously run a matched-field algorithm to localize submarine sources in a trip-wire configuration.

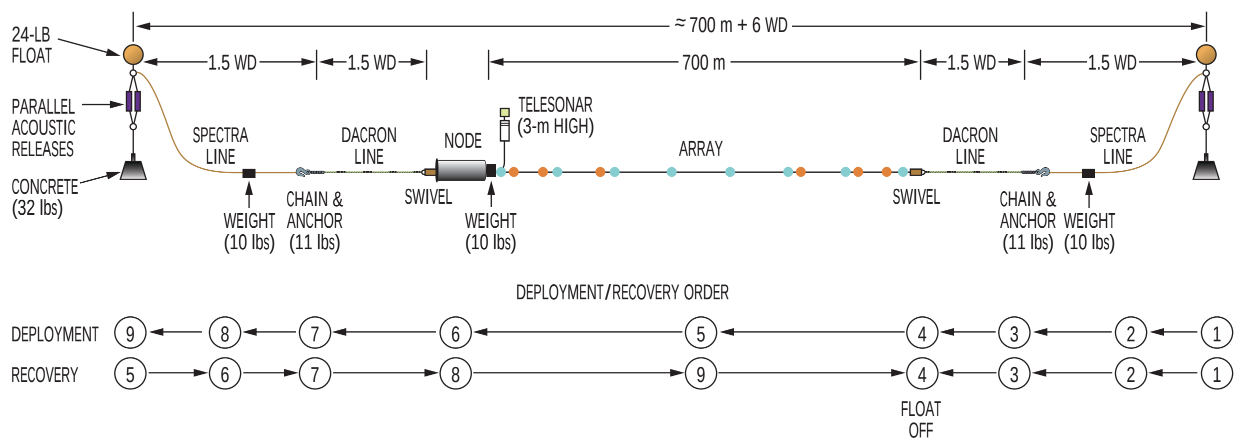

FIGURE 2. Hydra array configuration and deployment and recovery order.

CABLE DESIGN

The Hydra cable (Figure 3) uses four conductors for power and ground, with a fifth for data, and a sixth for telemetry synchronization. The specific gravity of 2.3 is sufficient to prevent current induced cable movement on most sediment types. With an overall cable diameter of 0.47 cm and weight in air of only 31.1 grams/meter, the array can be handled by two people and shipped as excess air baggage.

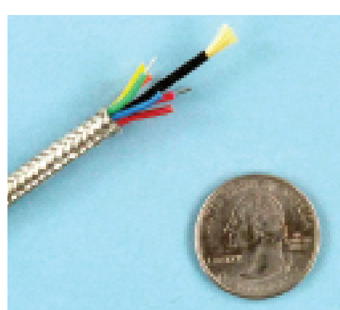

FIGURE 3. The Hydra cable consists of six 28-AWG (American Wire Gauge) conductors around a center Kevlar-strength member. The cable was designed to be very flexible and incorporates a free-flooding tinned copper braid shield overall.

ACOUSTIC SENSOR DESIGN

The Hydra acoustic sensor (Figure 4) is composed of a small, air-backed, piezoelectric hydrophone with a sensitivity of –187 dBV/uPa. A two-stage, low-noise (50 dB/uPa/root Hz over the full bandwidth), low-power, 3-volt preamplifier provides a gain of 50 dB from 10 to 200 Hz. A unity gain anti-alias filter follows the preamp. A 16-bit analog-to-digital converter samples the filter output at 600 samples per second. All digital telemetry is handled by a low-power field programmable gate array (FPGA).

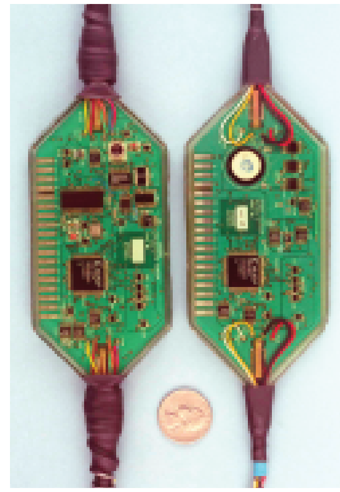

FIGURE 4. The acoustic (right) and non-acoustic (left) sensor circuit boards shown above are enclosed in a thin plastic form and filled with low viscosity polyurethane for waterproofing. Weights are added at the cable entrance and exit points to increase the package specific gravity to 1.8.

NON-ACOUSTIC SENSOR DESIGN

Non-acoustic sensors are distributed along both arrays to facilitate localization of the acoustic elements by measuring heading, tilt, and depth. In addition to the telemetry interface FPGA, each non-acoustic sensor uses a microcontroller to decode commands, control the conversion processes, and format and preprocess data. To conserve power, the microcontroller remains in sleep mode unless a command is received from the node, which controls the non-acoustic sensor sample rate (Kelp: once per minute; Hydra: once per hour). An 18-bit Sigma-Delta ADC, with integral gain and filter, samples the sensor outputs.

Array tilt (Kelp only) is measured by a two-axis accelerometer. This measurement also serves to correct the output of the three-axis heading magnetometer for tilt. The pressure sensor is exposed to ambient pressure via a small ceramic chimney filled with a pliable potting material.

TELEMETRY

Hydra and Kelp implement a noise-resistant digital time-division multiplexed telemetry scheme (Figure 5). The clock is partitioned into six acoustic data slots, one submultiplexed non-acoustic sensor slot, and a reset and command interval. Non-acoustic sensors, i.e., compass, tilt, temperature, and pressure, are multiplexed into the engineering sensor slot. The reset and command interval synchronizes the sensors and allows the node to send commands to them. A low-power FPGA in each sensor detects the reset interval, and begins an ADC; acoustic sensor outputs are simultaneously sampled. Then each sensor counts clock edges and places its data on the data conductor when its turn arrives.

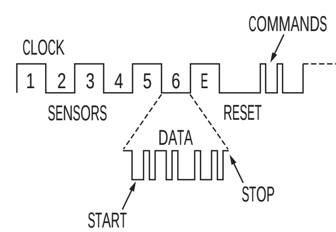

FIGURE 5. Hydra and Kelp implement a digital time-division multiplexing telemetry scheme. The FPGA in the node generates an array clock that delineates the data slot times assigned to a particular sensor.

Each data sample is an asynchronous bit stream with 2 start bits, 2 address bits to identify the data's origin, 16 data bits, and 1 stop bit. The node FPGA implements a universal asynchronous receive and transmit (UART)-style detector to decode the data stream. The data are then briefly buffered in parallel first in, first out (FIFOs) inside the FPGA and formatted for output to the DSP and data-recording subsystem.

NODE

The interchangeable Hydra and Kelp nodes (Figure 6) perform the following functions: (1) generate timing signals for multiplex synchronization, (2) send commands to the acoustic and non-acoustic sensors, (3) format the inbound digital data stream for the recording subsystem and for processing by the DSPs, and (4) report results via an underwater acoustic modem.

A significant effort was made to reduce size, weight, and average power consumption of the node. The Hydra node cylinder roughly measures 14 cm in diameter by 70 cm in length and weighs 20 kg in air and 2.7 kg in water. Each DSP board consumes approximately 3.5 watts; the balance of the circuitry, including the acoustic and non-acoustic sensors, consumes less than 1.5 watts.

Inside the canister is a collection of commercial and custom circuit cards. The node block diagram (Figure 7) shows two parallel data paths. One path is destined for the DSPs, and the other path for the raw-data recording subsystem. The block diagram also depicts the master controller card that features an 8-bit Microchip, Inc., microcontroller (PIC17C756A) that functions as a very reliable and flexible coordinator of most processes within the node.

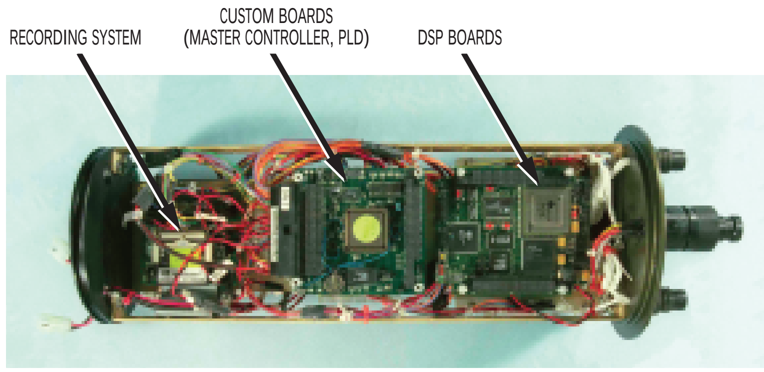

FIGURE 6. Hydra/Kelp node. The node design has evolved over 3 years and now forms a simple, yet powerful, flexible, modular, and expandable platform for evaluating advanced algorithms. Furthermore, reliable forward and backlinks, implemented through an underwater modem, provide scientists and engineers with solid control over mission execution.

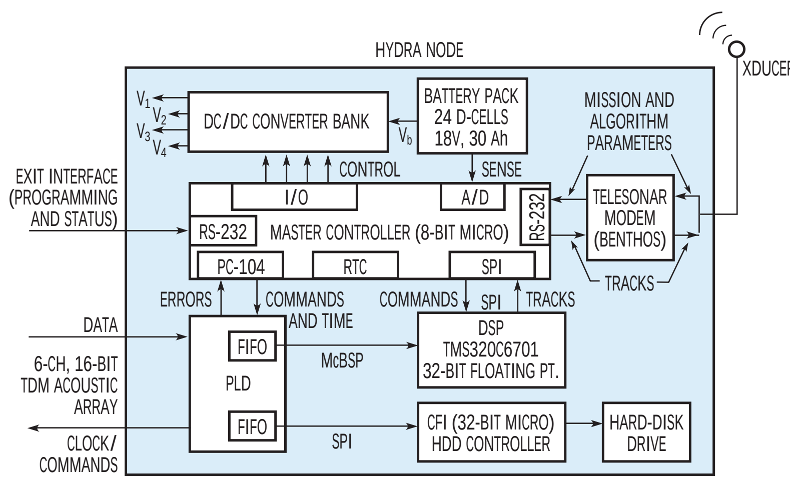

FIGURE 7. Hydra node block diagram.

DEPLOYMENT, RECOVERY, AND SYSTEM CONFIGURATION

Significant efforts have been made throughout the design process of all Hydra and Kelp subsystems to keep sizes and weights small compared to conventional acoustic-array systems. Thus, Kelp and Hydra can be deployed and recovered by only two people and one small rubber hull inflatable boat (RHIB) craft (Figure 2).

MATCH-FIELD TRACKING ON A DSP

Matched-field tracking solves for the position, course, speed, and depth of an underwater sound source by correlating acoustic spectra observed at known hydrophone locations with modeled spectra from hypothetical sound sources at various points within a five-dimensional search grid over a short processing epoch. Historically, this has been computationally and operationally demanding. Normal-mode acoustic modeling is typically time-consuming, memory-expensive, and must be tailored to each particular operating environment. The large number of Fourier frequency bins and target vector/depth grid points places a large computational burden on a processor.

Several design choices made it possible for an MFT algorithm to run in real time in an autonomous trip-wire system. First, the number of Fourier bins considered was reduced to the eight strongest 0.07-Hz-wide frequency bins from an assumed narrowband threat. Second, a two-path Lloyd's Mirror-based spectral model served as a simple, yet robust, replacement for the normal-mode approach. Third, processing epochs were 3 minutes long. Fourth, the MFT evaluated each incoming track in a search grid 1000 meters wide and 2000 meters long, offset 500 meters from the receive array. Finally, the algorithm was ported to Texas Instruments' TMS320C6701 32-bit floating-point DSP, which served as a capable low-power processing device.

A submerged target track was declared if its correlation exceeded a 70% threshold. Figure 8 illustrates MFT results for two submerged source crossings of a Hydra system in 164 meters of water off Halifax, Nova Scotia.

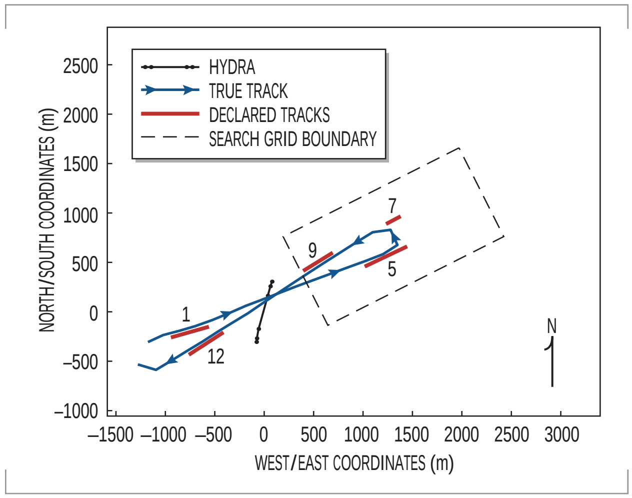

FIGURE 8. Real-time MFT over Hydra. The 4-knot, 46-meter deep source crossed Hydra twice during 12 epochs. Submerged tracks were declared for epochs 7 and 9 using the search grid shown for incoming targets. Tracks for epochs 1, 5, and 12 are derived by reorienting the grid, in situ, with Telesonar.

ADVANCED PROCESSING

For engaging threats with negligible narrowband energy, an alternative model-based process has been developed for targets with broadband signatures. This advanced process performs waveform cross-correlations for all hydrophone pairs. The key is to exploit the distinct correlation peaks associated with a multipath arrival structure as a function of range and depth. This is a distinctive fingerprint of the source location. Figure 9 shows the measured range-dependent multipath arrival structure from a towed source twice crossing Hydra off the coast of San Diego. Figure 10 shows a modeled version of this same array crossing, and Figure 11 shows the result of stacking slices versus depth at each time epoch during the array crossings.

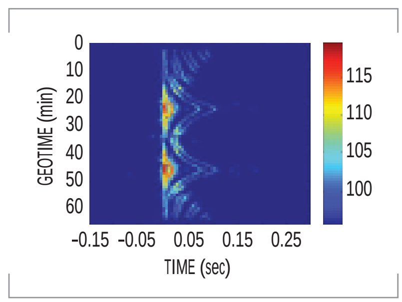

FIGURE 9. Measured multipath at a single Hydra array element during two array crossings. Note that the multipath is a distinctive fingerprint of source location.

SUMMARY

Hydra and Kelp were the first underwater passive acoustic autonomous array systems to implement an MFT algorithm in real time. The ultra-lightweight, low-power, array sensor system was the result of 20 years of research and development in underwater acoustic surveillance systems at SSC San Diego. The digital array and processing capabilities in the node represent a state-of-the-art, flexible, and modular platform for evaluating advanced processing algorithms.

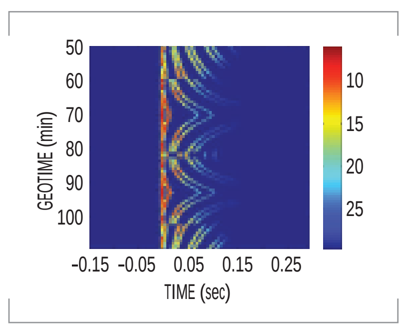

FIGURE 10. Modeled multipath at a single Hydra array element during two array crossings. The model accurately reconstructs the measured multipath shown in Figure 9.

ACKNOWLEDGMENTS

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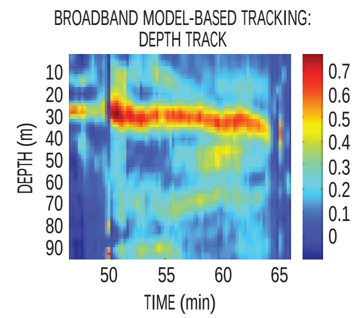

FIGURE 11. Advanced processing of broadband signature reproduced known source depth of 30 meters. Source was similarly tracked in x and y. These tracks were based on matching measured and modeled cross-correlation waveforms.

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